UNDERSTANDING PERMANENT MAGNET MATERIALS; AN ATTEMPT AT UNIVERSAL MAGNETIC LITERACY

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Abstract: The purpose of this paper is twofold. First, to review the basic terminology of permanent magnets and the salient characteristics of four commercially-viable families of permanent magnet materials. Second, to examine the methods and references available for teaching the basics of permanent magnets.

Key words: Permanent Magnets, Neodymium Iron Boron, NdFeB, Rare Earth Magnets, Magnetic Literacy

I. INTRODUCTION

Permanent magnet materials are incorporated in a device for only one reason, to increase magnetic flux. The flux may be necessary for one of the following purposes

- for detection, as it is in sensors
- to assist in creating a force or torque, as it does in motors, actuators and speakers
- to generate a voltage as it does in generators and alternators
- to create a magnetic field as it does in Magnetic Resonance Imaging (MRI) systems and electron beam devices.

While the materials available for permanent magnets continue to improve, their basic function remains the same.

II. THE THREE VECTORS

Most magnetic behavior is described in terms of three interrelated vector quantities.

B **-** Magnetic induction or flux density. A vector quantity, describing the concentration of magnetic flux at a point in space, expressed in terms of flux lines per unit of cross-sectional area. This quantity is reported as Gauss in CGS (centimeter-gram-second) units and as Tesla in SI (Système International d'Unités) units. [1]

H - Magnetic field. A vector, describing the magnetic field created by a field source, current moving through a wire or a permanent magnet, for example. Correct units are Oersted in CGS and Ampere-turn/meter (A/m) in SI.

M - Magnetization. A quantity describing the magnetic state of the material, representing the vector sum of individual atomic magnetic moments per unit volume. Magnetic moments arise from unpaired spinning electrons, typically in the 3d or 4f electron shell of each atom. The CGS unit for M is emu/cm^3 (emu = electromagnetic unit), although $4\pi M$ is in Gauss, the SI unit for M is A/m.

The three vectors are not independent, but are related. Induction is a combination of magnetization and magnetic field, but the exact relationship is slightly different between the two systems of units.

$$B = H + 4\pi M \quad \text{(CGS)} \qquad (1)$$

or

$$B = \mu_0 H + \mu_0 M \quad \text{(SI)} \qquad (2)$$

and

$$J = \mu_0 M \qquad (3)$$

Even though the B and $4\pi M$ are called Gauss, and H is called Oersted, equation (1) makes it clear that Gauss and Oersted are dimensionally equivalent. It is not unusual to hear someone refer to the intensity of a magnetic field in Gauss, although strictly speaking, it is not correct. The constant μ_0, where $\mu_0 = 4\pi \times 10^{-7}$ Tesla-m/A, that appears in equations (2) and (3) is called the permeability of free space and appears only in SI units. The quantity J, used in equation (3) is also a magnetization like M, although it is sometimes called a polarization, similar to the electrostatic quantity. The correct unit for J is the Tesla.

III. MAGNETIC HYSTERESIS

All magnetic materials, from the softest to the hardest, display hysteresis, with hard magnetic materials showing the greatest hysteresis. A word of Greek derivation, hysteresis describes the observation that magnetic materials are highly nonlinear, meaning their response to a stimulus lags behind in a repeatable manner. The stimulus in this case is an applied magnetic field and the material's response is the magnetization or induction.

A complete major hysteresis loop is shown in Figure 1. The x-axis shows the applied magnetic field, H, and the y-axis shows magnet's internal response, the magnetization, M. Starting from the origin, magnetization increases with increasing field, until a maximum is reached, defined as the saturation magnetization, M_s. The minimum field necessary to achieve saturation is called H_s; it is an important parameter although frequently ignored and difficult to define precisely. As the field is reduced to zero, we find much of the magnetization remains, defined as B_r, the residual magnetization. As the applied field becomes negative, we find that a significant field is required to reduce the magnetization to zero, defined as H_{ci}, the intrinsic coercive field. Higher negative field will saturate the sample in the opposite direction and a symmetric pattern can be seen in the rest of the curve that finally closes back on itself in the first quadrant.

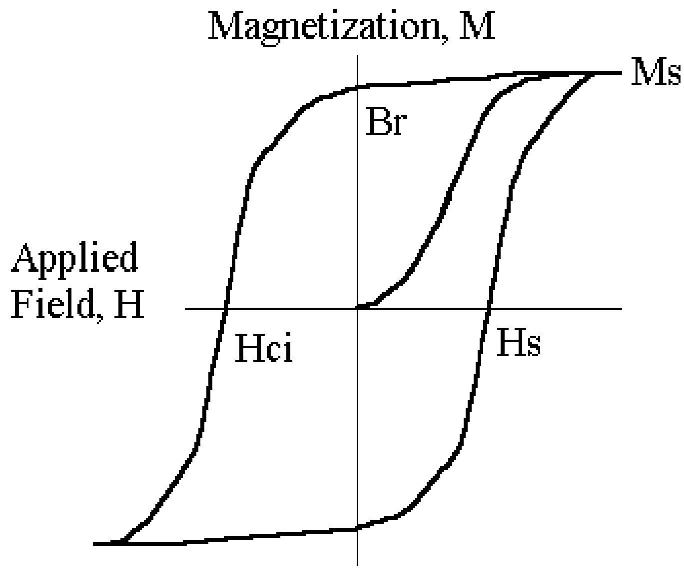


Figure 1. Major Hysteresis Loop, M vs. H

The loop in Figure 1 is a major hysteresis loop because sufficient field is applied to saturate the sample in both directions, making the enclosed area as large as possible for the sample in question. Applying a larger maximum field does not affect the size of the loop, nor does it yield any additional information. Data supplied about magnetic materials should be based on a major hysteresis loop, unless clearly stated otherwise.

Applying a smaller maximum field, one that does not fully saturate the sample, yields a minor loop. Typically, minor loops should be avoided, as the size and features of a minor loop depend on the maximum field supplied and not solely on the magnetic properties of the sample.

A very similar presentation is shown in Figure 2. This time, flux density, B, which is the externally available magnetic flux, is plotted against the applied field. Instead of flattening out at high field, this curve assumes a fixed and constant slope. The residual magnetization, B_r occurs at the same place, but the field to reduce the flux density to zero, H_c, is less than H_{ci}. The B vs. H curve also gives the energy product, $(BH)_{max}$, the largest product of B×H in the second quadrant.

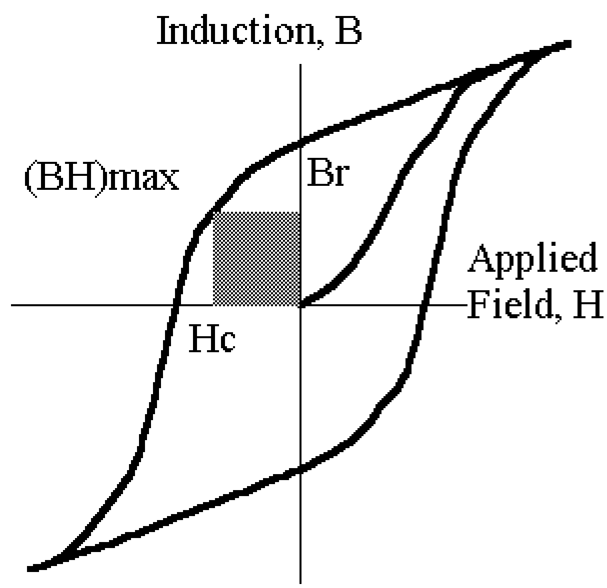


Figure 2 Major Hysteresis Loop B vs. H

Because there is some redundancy in showing the complete hysteresis loop, and there can be difficulty in applying enough field to saturate the sample, the standard convention is to show just the second quadrant, to show both the B and M curves together and to call them demagnetization curves, see Figure 3.

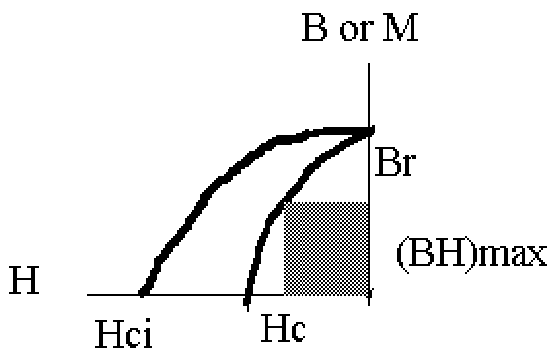


Figure 3. Second Quadrant Demagnetization Curves

Assuming ideal behavior, meaning no decrease in magnetization once a sample is saturated, all the following equations are true as equalities. When real cases are considered, less than applies.

$$4\pi M_s \geq B_r \text{ (CGS)} \quad (4a)$$

$$\mu_0 M_s = J_s \geq B_r \text{ (SI)} \quad (4b)$$

$$B_r \geq H_c \text{ (CGS)} \quad (5a)$$

$$B_r \geq \mu_0 H_c \text{ (SI)} \quad (5b)$$

$$H_{ci} \geq H_c \text{ (CGS and SI)} \quad (6)$$

$$(B_r/2)^2 \geq (BH)_{max} \text{ (CGS)} \quad (7a)$$

$$(B_r/2)^2 \geq \mu_0 (BH)_{max} \text{ (SI)} \quad (7a)$$

IV. THE FOUR FAMILIES OF PERMANENT MAGNETS

The properties of the major permanent magnet materials are summarized in Table I. Each material has at least one reason to maintain commercial interest. Ferrite magnets have the lowest cost in terms of dollars per kilogram of material, but they have the poorest magnetic properties and H_{ci} decreases as the temperature decreases. Alnico magnets have the lowest temperature coefficient of B_r and the highest maximum operating temperature, but they

Table I. The Four Families of Permanent Magnets

	Ferrite	Alnico	SmCo		NdFeB			
Property	Ceramic 8	Alnico 5	REC-20	REC-26	HS-42AV	MQ1-B	MQ2-E	MQ3-F
B_r (kG)	4.0	12.5	9.0	10.5	13.1	6.9	8.25	13.1
α (%/°C)	-0.18	-0.02	-0.05	-0.03	-0.12	-0.105	-0.10	-0.09
$(BH)_{max}$ MGOe	3.8	5.5	20	26	42	10	15	42
H_{ci} (kOe)	3.3	0.64	20+	10+	14	9	17.5	16
H_{ci} as temp falls	Worse	Better	Better	Better	Better	Better	Better	Better
Tooling cost ($)	50 –100K	1-5K	20 K	20 K	20 K	5K	10K	15 K
H_s (kOe)	10	3	20	30	25	35	45	35
T_c (°C)	450	890	727	825	310	360	335	370
Electrical conductivity	Poor	Good	Good	Good	Good	Good	Good	Good
Grinding required?	Yes	Yes	Yes	Yes	Yes	No	No	No
$/lb	$	$$	$$$$	$$$$	$$$	$$	$$	$$$

Notes : The quantity α is the reversible temperature coefficient of B_r.
The field required to saturate is H_s.

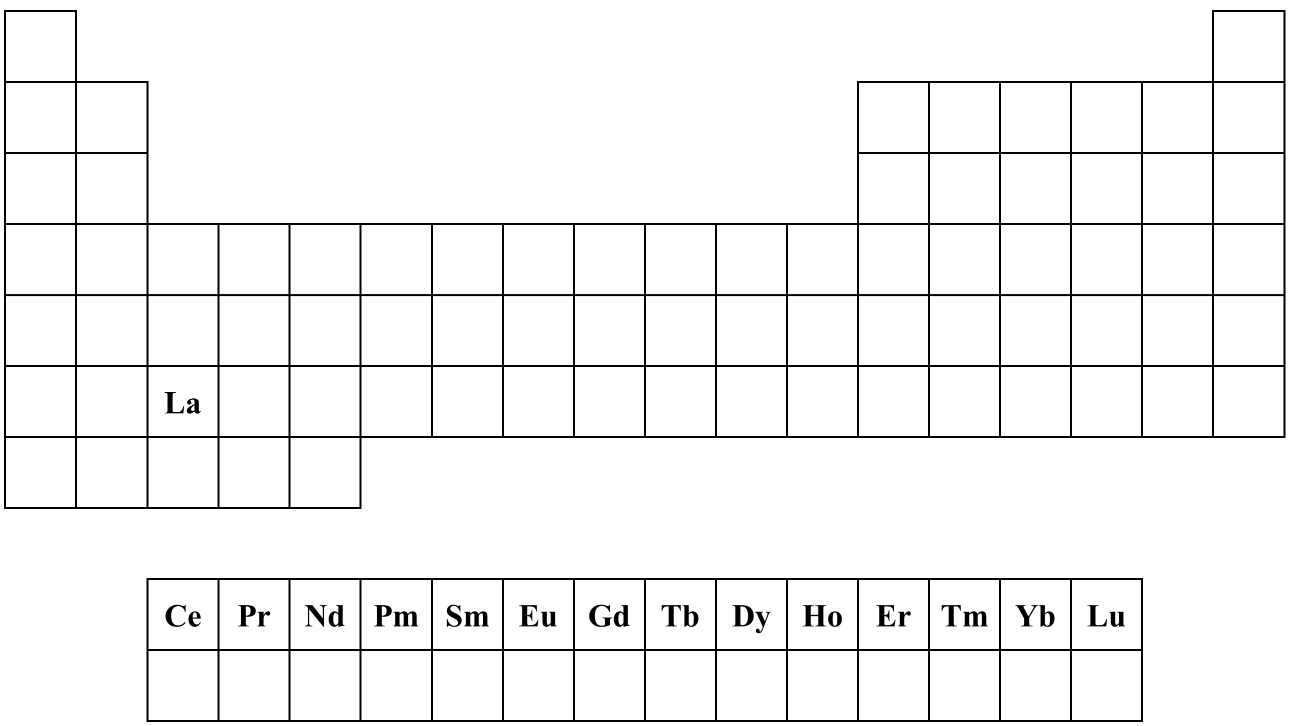
have the lowest H_{ci}. Samarium cobalt magnets, both the $SmCo_5$ and the Sm_2Tm_{17} (where Tm is a combination of mainly transition metals, Co, Fe, Cu and Zr or Hf) compositions, have exceptionally high H_{ci} values and relatively low temperature coefficient of B_r, but the high cost of both samarium and cobalt makes these the most expensive magnets in use today. Neodymium Iron Boron magnets come in four distinct varieties: bonded, hot pressed, die upset and sintered. In general neodymium magnets offer the highest $(BH)_{max}$ and more recently, the best value in terms of flux per dollar. Corrosion resistance and maximum operating temperature have been long standing objections, but generally overcome with appropriate coatings and an understanding of the thermal properties of NdFeB, when designing a new device.

V. THE RARE EARTHS

Magnets based on the rare earths (the lanthanides) have been around since the 1960's, but they are still considered exotic materials by some, even though significant ore deposits are found in many locations around the world and they are used in many common applications. Table II shows their position on the periodic table and Table III spells out the names, atomic numbers and presents a way to memorize the names.

Neodymium is a particularly good choice for a permanent magnet. It is the third most abundant lanthanide, behind cerium and lanthanum. And unlike its more abundant neighbors, currently there is more supply than demand for neodymium, helping to keep prices low today and into the foreseeable future.

Table II. Periodic Table of the Elements



The situation with samarium is different. It is less abundant that neodymium, by a factor of roughly 20:1, and the metal is a little more difficult to handle. At the moment, demand for samarium is less than supply, but a slight change in market could tighten things, as it has in the past.

There are five important lanthanide facts that are worth knowing about the rare earths.

- Lanthanides are found together in nature, hence the name rare earths
- Bastnasite and monazite are the two main ores
- Rare earth oxides are the most stable oxides known
- Chemically all the lanthanides are very similar
- But magnetically they are quite diverse, showing an incredible range of magnetic behavior

Table III. The Lanthanide Elements, Their Atomic Numbers and a Convenient Mnemonic Device. [2]

Element	Atomic Number	Associated Word
Lanthanum	57	Lazy
Cerium	58	College
Praseodymium	59	Professors
Neodymium	60	Never
Promethium	61	Produce
Samarium	62	Sufficiently
Europium	63	Educated
Gadolinium	64	Graduates
Terbium	65	To
Dysprosium	66	Dramatically
Holmium	67	Help
Erbium	68	Executives
Thulium	69	Trim
Ytterbium	70	Yearly
Lutetium	71	Losses

VI. EDUCATION ON MAGNETIC MATERIALS

One oddity about the permanent magnet industry is that so few people involved in the business receive any formal training on the subject, less than 1% studied the subject at the university level. Typically training is received when one enters the business and any subsequent training is done on an ad hoc basis. There appear to be three reasons. First, very few universities have research programs or any other interest in permanent magnets, hence there are few professors, few students and few graduates. Secondly, the subject has a reputation for being very difficult. Many give up easily, too easily. The terminology is both complicated and arcane, requiring patience to master. Third, there is a general lack of good references, especially for a person early in the learning process.

I have promoted the concept of "universal magnetic literacy". The idea that everyone working with permanent magnets has an obligation to understand a few basic concepts of magnetism on their own and not have to rely exclusively on the technical expertise of others to do their job. Of course, this is really the first step on the road to fluency and independent critical analysis. Just as we accept the concept that everyone should learn to read and write to function in the world today, universal magnetic literacy is important for the continued health of our industry.

Consider each of the following perspectives:

A. Students

While there may be interest in learning about magnetic materials, several concerns may impede the process.

- People come from varying backgrounds, often with limited mathematical capability. This makes group teaching difficult.
- Limited time.
- Interest in just a few narrow topics, often prompted by demands of the job, even though a broader understanding would be more useful.

B. References

While there are many excellent texts on magnetism [3-9], just a few are good reference materials for training people at the beginning level. My personal preference is to use Magnet Story [9], with a glossary and other materials. Written by the Bonded Magnet Association of Japan and first published in Japanese, Magnet Story provides a very basic and nonmathematical treatment of most of the major areas, with a nice historical perspective. Some of the translations from Japanese to English are wonderful.
At the beginning level, there is a clear need for a new book.

Some comments on each of the references may help the reader decide which books to examine after Magnet Story.

Campbell [3] has written an excellent text for electrical engineers interested in designing devices with permanent magnets. It is very mathematical.

Livingston's book [5] is an entertaining first person description of the science of magnets in laymen's terms, without mathematics.

Cullity [4] is the best reference book on materials and the basic physics of magnetism, although some of the information is now dated. It has the clearest explanations of any reference, above all the section on self-demagnetization.

Moskowitz [6] has good detailed descriptions of basic magnetic designs, especially holding magnets. There is no coverage of rare earth magnets, but some extrapolation from ferrite is possible.

McCaig and Clegg's book [7] is good general reference like Cullity [4] and a little more up to date.

Parker [8] has an excellent section on the history of permanent magnets. It is detailed and mathematical, with good design and material information.

C. Technologists as Teachers

While a few people understand the technology, teaching magnetism is not easy and often people do not have the aptitude for it. First, it is difficult to properly assess the correct technical level of a group, for effective communication. Second, it is often difficult to put some very difficult concepts in to understandable language. Third, some people are uncomfortable teaching.

More qualified technologists need to take the time to become proficient teachers and share their vast knowledge with others.

D. Classes

There seem to be three distinct approaches taken in teaching magnetics.

1. Give someone a book and provide little additional instruction.
2. Provide intense one-on-one sessions. Typically, one or two days in length.
3. Give formal lectures with a book and other materials.

Each approach has its limitations. The first approach assumes that someone can gain an understanding through reading. Of course this may happen, but it takes a great deal of discipline to work well. It has the advantage that little or no direct teaching is required. The second approach tries to convey a great deal of information a brief period of time. While some information will be absorbed this way, the general overall efficiency is quite low and retention is limited. Both the teacher and the student feel time pressure in this scenario. The third approach works well when all members of the class are at roughly the same level in terms of educational background, something that doesn't happen very often. Also, the same lectures may be used over and over again.

My personal preference is to use Magnet Story, along with some class notes and a glossary [10], in a much less formal setting, meeting for about an hour at a time, over the course of two or three weeks. Much more learning takes place in eight one hour meetings than a single eight hour session. Certainly time is required between classes to allow students to read and think. Learning about magnets is a very nonlinear activity, meaning that one becomes better with over time, but usually not immediately and not in any way proportional to the effort expended. It can be particularly slow at the beginning, mainly because the concepts and terminology seem foreign. Just a few brief, specific lectures are used, with most of the time allocated to question and answer sessions. These are important to avoid leaving anyone behind in the discussion. The questions reveal the level of understanding and the specific areas of interest. The questions are almost never the ones anticipated before class. This approach seems to work well with people from a variety of backgrounds and interests.

VII. CONCLUSIONS

- Understanding magnetic materials begins with understanding their hysteresis loops.
- Each type of permanent magnet material offers one or more reasons to consider it for use. Our obligation is to understand these reasons, in order to make good material selections.
- The lanthanide elements are not rare after all, even though they are called rare earths. They are used in a wide array of applications, including permanent magnets.
- Magnetic education is necessary for our business to prosper and is in need of more resources and practitioners.

REFERENCES

1. *Standard for Use of the International System of Units (SI): The Modern Metric System*, IEEE/ASTM SI 10-1997.

2. Barry T. Kilbourn, private communication

3. Peter Campbell, *Permanent Magnet Materials and their Application*, Cambridge University Press (1994).

4. B. D. Cullity, *Introduction to Magnetic Materials*, Addison-Wesley, Reading, MA (1972).

5. James D. Livingston, *Driving Force, The Natural Magic of Magnets*, Harvard University Press, Cambridge, MA (1996).

6. Lester R. Moskowitz, *Permanent Magnet Design and Application Handbook*, Robert E. Kreiger (1986).

7. M. McCaig and A. G. Clegg, *Permanet Magnets in Theory and Practice*, Pentech Press, London, (1987).
8. R. J. Parker, *Advances in Permanent Magnetism,* John Wiley & Sons (1990).

9. *Magnet Story*, Electronic Materials Manufacturers Association of Japan (EMAJ) 1998.

10. S. R. Trout, *A Glossary of Magnetic Terms*, in progress.

Stanley R. Trout received the B.S. degree with honors in physics from Lafayette College in 1973. Under the direction of C. D. Graham, Jr., he earned an M.S. degree in 1976 and Ph.D. degree in 1979, both in metallurgy and materials science from the University of Pennsylvania.

For the last twenty-five years, he has worked in the permanent magnet and rare earth industries. Among his noteworthy projects have been the use of permanent magnets in Magnetic Resonance Imaging (MRI), break-away goal posts for ice hockey, the use of Helmholtz coils for magnetic measurements, and the application of hydrogen decrepitation for size reduction of neodymium iron boron ingots. Currently he is the applications engineer for Magnequench International, where he has been employed since 1997. Dr. Trout is a senior member of the IEEE Magnetics Society, a member of the Society of Automotive Engineers and chairs the Permanent Magnet Technical Committee of the Magnetic Materials Producers Association. He has been a registered professional engineer in the Commonwealth of Pennsylvania since 1978.